Fermi National Accelerator Laboratory

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Muon Fluence Measurements During the 1987 - 1988 Fixed-Target Run

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Introduction

Muon fluence (muons-cm^{-2}) was measured downstream of the experimental area beam lines at a number of locations including Route 38 (Roosevelt Road) in West Chicago, just beyond the Fermilab site boundary. The goal was to study the transport of high-energy muons through earth and air, and at the same time obtain an estimate of the yearly off-site radiation exposure to any member of the general population due to accelerator produced muons. The current run saw the initial operation of four new beam lines - MW, MP, NM, and PB - as well as continued use of previously commissioned beams in all three areas - Meson, Neutrino, and Proton. This report describes the muon fluence profiles at the various locations and the site boundary dose equivalent values. Similar measurements for previous fixed-target runs have been reported.[1-3] Subsequent reports will discuss muon production and transport phenomena.

Measurements

The measurements were performed with the Mobile Environmental Radiation Lab (MERL), as described previously.[1-3] Muons were detected by a pair of 0.64 cm thick plastic scintillator paddles, with transverse dimensions of 20.32 cm by 20.32 cm. The paddles were separated by 15 cm with a 2.54 cm thick aluminum plate placed in the gap to remove δ-rays. They were located in the vehicle at a height of about four feet (1.2 m) above the ground. Standard electronic modules were used to record on scalers both singles and coincidence events from the two detectors. The scalers were gated on during both beam-on (a 23 sec beam spill period) and beam-off time periods in synchronization with the accelerator cycle. Counts during the beam-off period following each spill were used for background subtraction.

Data were collected at a number of locations on the Laboratory grounds and at Route 38, in West Chicago, which is just beyond the site boundary downstream of the experimental areas. Table 1 is a description of the reference locations. Measurements were performed by scanning across the muon radiation field on a line approximately normal to an extension of the beam line. Detector counts were recorded for at least two beam spills at each position along a scan at all locations. Primary beam intensity information was determined with secondary emission monitors (SEM) upstream of the target positions on the beam lines. Intensities were recorded separately for each spill.

Muon fluence is based on singles rates in the scintillator paddles. Even though two paddles operated in coincidence may provide a more sensitive measure of the existence of muons in weak fields,[3] the background-corrected singles rate determines the muon flux. The coincidence-to-singles ratio depends upon the direction of the incident muon beam relative to the normal to the paddle surface; a value close to unity means that the muons are incident almost perpendicular to the paddle, while at the other extreme a value of 0.1 suggests that they impinge isotropically from all directions.[3]

Table 2 lists both the average proton intensity per pulse and the total number of protons delivered to each beam line for both 1987 and 1988. Muon dose equivalent at the site boundary associated with the measured fluence is shown for each beam line in Table 3 for the total proton beam delivered. The values are based[4] on a fluence-to-dose equivalent conversion factor of 2.5×10^4 muons cm^{-2} $mrem^{-1}$.

Meson Area Beams

The distribution of muon fluence as a function of lateral distance, referenced as indicated in Table 1, is shown in Figs. 1, 2, and 3 for Meson area beams. The results are normalized to 1×10^{12} incident protons per spill. At locations 1 and 3 the MW and MC profiles were determined separately for each beam. At location 2, both the MW and MP profiles were measured with MC off. However, the MC scan could only be obtained with MW running at the same time. The MP beam line operated only with MC off, and for fewer days during the run, so that time did not allow observations at the site boundary. No muons associated with the ME beam line were seen, in agreement with previous observations.[3] The ME experiment E772, like E605 in past runs, employed a massive magnet to deflect muons vertically, thus significantly reducing fluence at the operating height of the MERL paddles.

Table 4 shows the maximum muon fluence, coincidence-to-singles ratios, and the approximate distance from the primary targets which are expected to be the main location of muon production.[5] The maximum annual dose equivalent at Route 38 (the site boundary location) for the total number of protons incident on each beam line is indicated in Table 3. Non-zero values are associated with both MW and MC. Although the MC dose equivalent for 1987 is about a factor of two larger than during the 1985 run, it remains less than the Director's 10 mrem annual goal.

Proton Area Beams

Average proton intensity per pulse was significantly lower for PW, PC, and PE beam lines during 1987-1988 than during the 1985 fixed-target run. Even so, muons associated with both PW and PE beam lines were clearly observed at Eola Road, location 4, as shown in Fig. 4. On the other hand no fluence was seen at the site boundary location, Fig. 5. The muon peak previously observed[2,3] for PW during the 1984 and 1985 runs was noticeably absent, and the site boundary dose equivalent values indicated in Table 3 should be taken as upper limits only. The newly commissioned PB beam contributes significant muon fluence in back of the experimental hall (Fig. 6) and at Eola Road. But again no peak was observed at the site boundary location. Primary target locations in Table 3 were taken as enclosure PW6 for the PW beam, and enclosures PE3 and PB4 for the other two beams.

Fig. 7 shows PW muon profiles at Eola Road that correspond to different operating conditions for the beam line. Both refer to positive pion E705 runs but the scan labelled 1/13 represents a condition in which the hadron beam was dumped between the target and the momentum slit, while 1/17 refers to runs in which no dumping occurred, so that there was increased pion decay and a correspondingly larger muon fluence. This Figure illustrates that in the measurements reported here muon profiles could change whenever operating conditions were drastically varied. Mostly, however, reproducibility was good when normal operations were in progress.

NM, and Neutrino Area Beams

Significant muon fluence was observed downstream of the new Muon Lab. These results are displayed in Figs. 8, 9, and 10. Generally two scans are shown at each location. The first (labelled TOR.OFF) represents running conditions in which the muon beam exiting the E665 experiment impinges directly onto the earth shield in back of the Lab. The fluence is large and the peaks in the distributions are quite narrow - about 60 feet wide (FWHM) at the site boundary. Coincidence-to-singles ratios (Tables 3 and 4) are over 0.7 even at Route 38, which suggests that the muons remain as a well-collimated beam even after penetrating ~12000 feet of earth.

The second profile shown on each figure represent observations made after the addition of two toroidal "spoiler" magnets in back of the experiment to intercept the muon beam and deflect it downwards before it enters the earth shield. As observed the effectiveness of the magnets in reducing muon fluence is dramatic; intensity is reduced by factors of 15 (Route 38), 18 (Powerline Road), and 20 (Kress Creek). At Kress Creek the lateral distribution is widened, and at the two most distant locations it is broadened and the centroid shifted so that the peak almost disappears into a broad background contribution that may be related to halo around the original muon beam, and/or to muons associated with the NE and NT/NH beam lines.[6] Calculations with CASIM are in progress[7] in attempts to understand the observed distributions.

The site boundary dose equivalent for 1987 is the sum of the no-toroid and toroid-on values, shown in Table 3. It is based on the total number of protons recorded on the NM2 SEM up to 11/30/87 (no-toroid observations) and from 12/1/87 to 12/31/87 (toroid-on). The value 13.1 mrem is about 30% higher than the Fermilab Director's goal to limit off-site exposures to 10 mrem per year.

Muon fluence observed in back of the new Muon Lab is shown in Fig. 11. It is not clear at present whether this distribution arises solely by multiple scattering of the muon beam incident onto the earth downstream of E665, or contains a sizeable contribution from muons deflected out of the ground by the toroid in enclosure NMØ, upstream of the experiment.

No muons associated with the NC beam line have been observed; this is not surprising since NC has been especially designed to attenuate muon flux to very small values. Muons from NE and NT/NH beam lines have probably been identified at the Eola Road location, as seen on Fig. 12. Muon production targets for both these beams are assumed to be primarily in Enclosure NE8 with that for NE, which receives about 2/3 of the incident protons, further west. It is likely therefore that the largest peak on the figure - the most westerly - is to be associated with NE.[8] Also seen on Fig. 12 is a small peak associated with the NM beam line; it probably arises from deflected muons of lower momenta than those selected in Enclosure NM5 for transport to the experiment.

There is some evidence that muons associated with NE and NT/NH are also observed at Powerline Road (location 6). Fig. 13 shows a muon profile measured when an access was in progress in the Muon Lab. Under such conditions beam is still recorded in the NM2 SEM, but no beam is delivered to the experiment. It is hard to understand the existence of the broad peak near-175 feet if it not due to NE and/or NT/NH beams. In fact, the peak intensity is in excellent agreement with the value from a $1/r^2$-extrapolation of the NE intensity at Eola Road (Fig. 12). Also, on Fig. 13, the possible small peak at about-420 feet is at the right lateral position to be associated with muons that arise directly at the target in Enclosure NM2 and travel in a straight line out to Powerline Road under access conditions in the Muon Lab.

Summary

Muon fluence and dose equivalent have been observed at the Fermilab site boundary for the MC, MW, and NM beam lines. For MC and MW, the 1987 annual dose equivalents of 2.9 and 1.2 mrem respectively, are less than the 10 mrem site boundary goal. For the new NM beam line, on the other hand, the observed value 13.1 mrem exceeded this operational goal. Indeed, it was this observation that necessitated the additional "spoilers" downstream of the E665 experiment. With these magnets in place, however, the 10 mrem goal should not be in jeopardy for future runs.

Acknowledgements

We wish to thank Don Cossairt and Steve Butala for assistance with some of the measurements and for useful and informative discussions. We thank John Larson and Tom Anderson for their efforts to keep the MERL electronics, telemetry system, and the truck itself operational.

TABLE 1

Description of reference locations. All positive distances shown on the Figures are to the east, negative to the west, of the reference point.

Location	Description
1	On road just north of MW experimental hall, MW9, referenced to the west end of MW9.
2	Along Wilson St., referenced to the MC beam stake. Note: Wilson St. intersects the MW beam line at an angle θ of ~54^{o}, MC at ~52^{o} and MP at ~49^{o}. The data were corrected by projecting along a line perpendicular to the beam lines.
3	Along Route 38, Roosevelt Road, on south side, referenced to the center of Town Road.
4	Along Eola Road, referenced from the center of the intersection with Road C - West.
5	Along Kress Creek, referenced as closely as possible to the intersection with an extension of the NM beam line (yellow stake).
6	Along Powerline Road, referenced as closely as possible to the intersection with an extension to the NM beam line.
7	On road just north of the Muon Lab, NMS, referenced as closely as possible to the intersection with the NM beam line extension.
8	On road just north of the Wide Band Lab, referenced as closely as possible to the intersection with the PB beam line.

TABLE 2

Proton Intensities

Beam Line	Average Beam Intensity for the 1987-1988 Run ($\times 10^{12}$/pulse)	Total Delivered Beam During 1987 ($\times 10^{17}$)	Total Delivered Beam During 1988 ($\times 10^{17}$)
PE	0.68	0.69	0.27
PB	1.09	0.64	0.64
PC	0.23	0.14	0.165
PW	0.47	0.45	0.28
ME	0.76	0.45	0.50
MC	0.76	0.77	0.21
MP	0.93	0.49	0.47
MW	0.89	0.68	0.66
NC	4.23	5.28	1.16
NE	0.61	0.77	0.23
NM (No-Toroid-to 11/30/87)	1.54	1.15	---
(Toroid)	---	0.61	0.71

TABLE 3

Results of Measurements at Route 38, the site boundary location. The fluence is given for 1×10^{12} protons incident on the appropriate SEM.

Beam Line	Distance from Primary Target (Feet)	Max Muon Fluence (muons-cm^{-2})	Conc. to Singles Ratio	1987 Annual Dose Equivalent (mrem)	1988 Annual Dose Equivalent (mrem)
MW	12069	0.44±0.15	0.60	1.20	1.16
MC	12022	0.94±0.02	0.60	2.90	0.79
PW	10280	0.04[a]		0.07	0.045
PE	10340	0.06[a]		0.17	0.065
PB	10260	0.02[a]		0.05	0.05
NM (No-toroid)	12158	2.77±.02	0.77	12.7	---
NM (Toroid-on)	12158	0.18±.01	0.64	0.44	0.51

[a]No peaks were observed on the muon distributions (see Fig. 5). These values are upper limits.

TABLE 4

Results of measurements at a number of locations for the various beam lines. All results are for 1×10^{12} protons incident on the appropriate beam line SEM.

Beam Line	Location No. & Dist. from Primary Target (feet)	Max Muon Fluence (muon-cm^{-2})	Coinc. to Singles Ratio	Location No. & Dist. from Primary Target (feet)	Max Muon Fluence (muon-cm^{-2})	Coinc. to Singles Ratio
MW	1, 1233	103.8±0.3	0.74	2, 1873	15.9±0.3	0.67[a]
MC	1, 1214	277.8±0.4	0.78	2, 1914	19.3±0.2	0.70[a]
MP	1, 1243	---	---	2, 2063	3.6±0.1	0.58[a]
PW				4, 2680	2.97±0.04[b] 7.4 ±0.2	0.68[b] 0.64
PE				4, 2740	4.29±0.06	0.67
PB	8, 1600	24.76±0.07	0.76	4, 2630	2.57±0.03	0.64
NE	4, 2188	48.5 ±0.1	0.81	6, 9788	2.76±0.15	0.77
NT/NH	4, 2188	17.0 ±0.1	0.82	6, 9788		
NM (No-toroid)	5, 8798	11.14±0.05	0.87	6, 10998	4.40±0.03	0.85
NM (Toroid-on)	5, 8798	0.59±0.01	0.70	6, 10998	0.27±0.01	0.81

[a]Coincidence counting rates corrected for efficiency; that is, the non-zero angle between beam direction and scintillator paddles (i.e., $\epsilon_{coinc}=1-(15/20.3)\cot\theta$, where θ is given in Table 1).

[b]The two values shown here represent two different running conditions. See Fig. 7.

Figures

Note: Muon fluence is given per 10^{12} protons incident on the appropriate beam line SEM. Negative (positive) numbers represent directions to the west (east) of the particular reference point (see Table 1).

1. Meson Area beam lines at location 1, i.e., in back of MW9.

2. Meson Area beam lines at location 2, i.e., along Wilson Street. The data were corrected by projecting along a line perpendicular to the beam line.

3. Meson Area beam lines at location 3, i.e., the site boundary.

4. Proton Area beam lines at location 4, i.e., Eola Road.

5. Proton Area beam lines at location 3, i.e., the site boundary. The most westerly data point is probably due to the NM beam line.

6. PB beam line at location 8, i.e., on road just north of the Wide Band Lab.

7. PW beam line at location 4 for two different running conditions (see Text).

8. NM beam line at location 5, i.e., Kress Creek, for both no-toroid and toroid-on runs.

9. NM beam line at location 6, i.e., Powerline Road, for both no-toroid and toroid-on runs.

10. NM beam line at location 3, i.e., site boundary, for both no-toroid and toroid runs.

11. NM beam line at location 7, i.e., road just north of the Muon Lab.

12. Neutrino Area beams at location 4, i.e., Eola Road. The results for NE and NT/NH are normalized to the NES SEM values; for the NM beam line, they are normalized to the NM2 SEM.

13. Neutrino Area beams at location 6 during an access into the Muon Lab, i.e., no muon beam accelerated. Proton beam is however incident on the NM2 SEM. The solid points are normalized to the NES SEM; open points to the NM2 SEM. The positions of beam line extensions are indicated by the arrows. NM2 represents the lateral position of Enclosure NM2 relative to the other beams indicated.

References

1. Cossairt J.D., 1981, "Recent Muon Dose Equivalent Measurements at Fermilab," Health Physics 45, 657.

2. Elwyn A.J. and Freeman W.S., 1984, Muon Fluence Measurements at 800 GeV, Fermi National Accelerator Laboratory, Batavia, IL, 60510, TM-1288.

3. Elwyn A.J., 1986, Muon Fluence Measurements at the Site Boundary for 1985, Fermi National Accelerator Laboratory, Batavia, IL, 60510, TM-1394.

4. Stevenson G.R., 1983, Dose and Dose Equivalent from Muons, European Organization for Nuclear Research, CERN, Geneva, Switzerland, TIS-RP/099.

5. There is some evidence that a small contribution to muon fluence at all three locations can be attributed to muon production in Enclosure MC2.

6. Generally, the intensity of protons incident on the NE beam line, recorded in the NES SEM, was lower by almost a factor of 10 than those incident on NM during these measurements.

7. Cossairt J.D., 1988, Private Communication.

8. The fluence associated with both NE and NT/NH is based on normalization to the NES SEM.

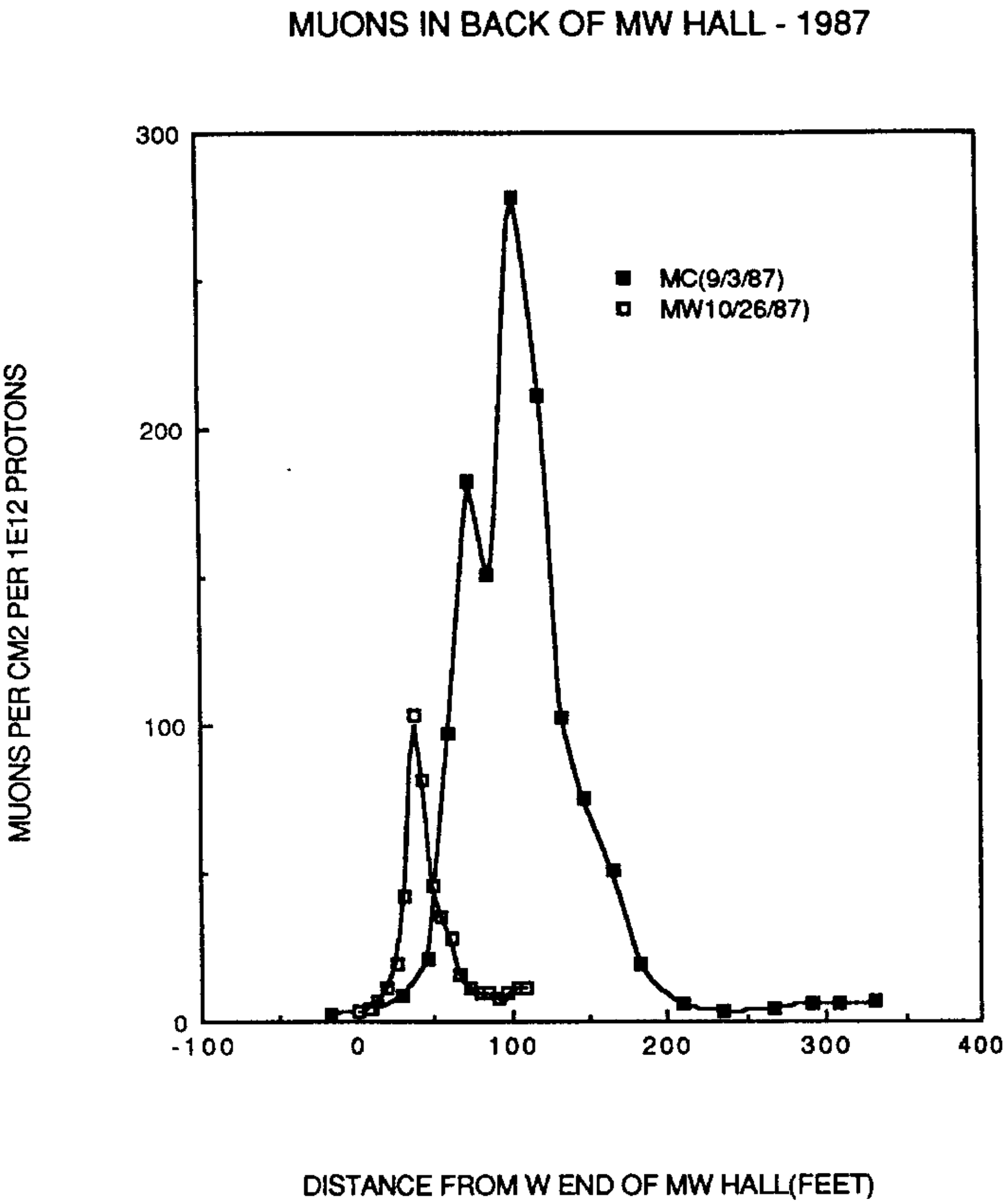

MUONS IN BACK OF MW HALL - 1987
MC(9/3/87)
MW10/26/87)
MUONS PER CM2 PER 1E12 PROTONS
DISTANCE FROM W END OF MW HALL(FEET)
300
200
100
0
-100
0
100
200
300
400

Fig. 1

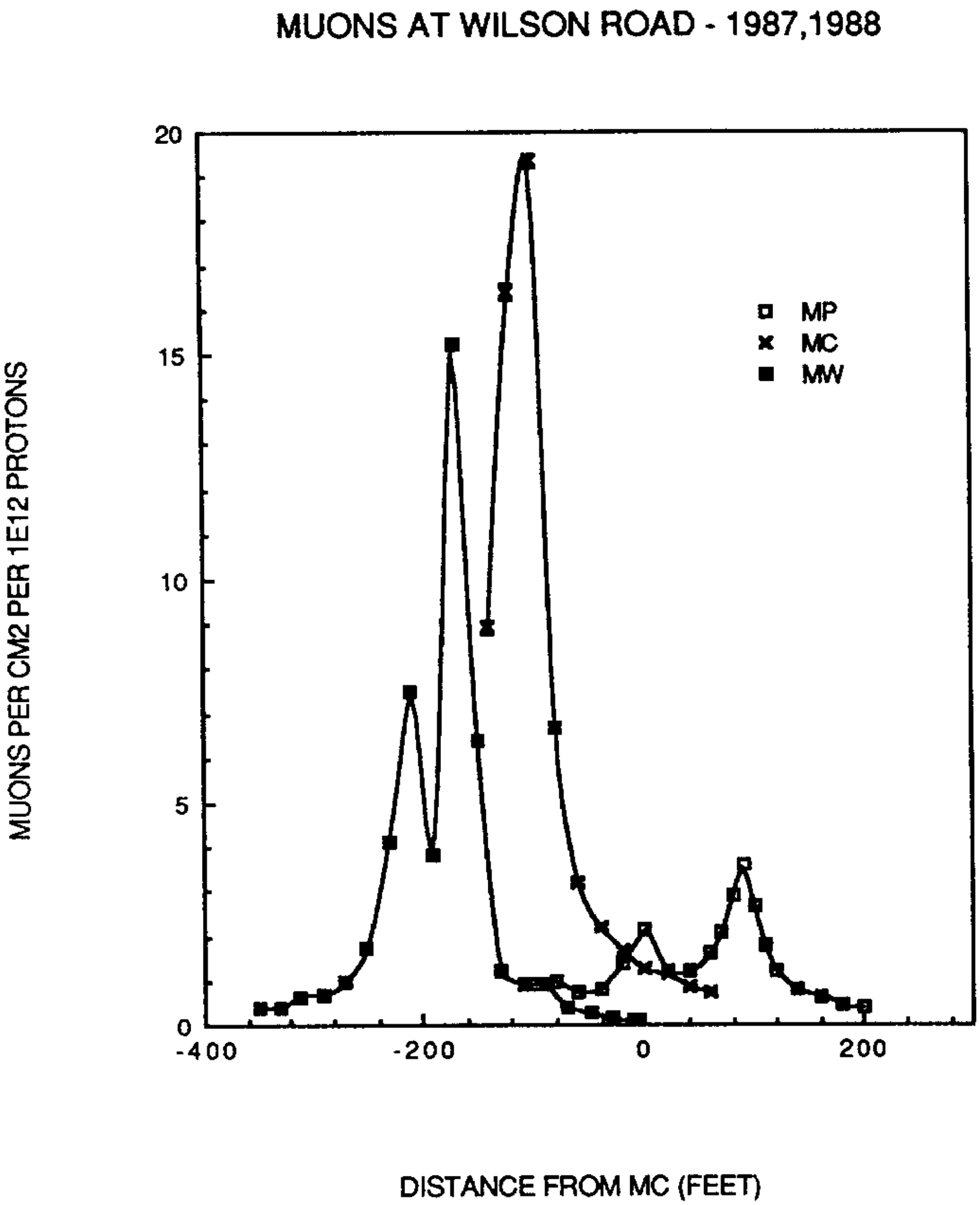

MUONS AT WILSON ROAD - 1987,1988
MUONS PER CM2 PER 1E12 PROTONS
DISTANCE FROM MC (FEET)
MP
MC
MW
20
15
10
5
0
-400
-200
0
200

Fig. 2

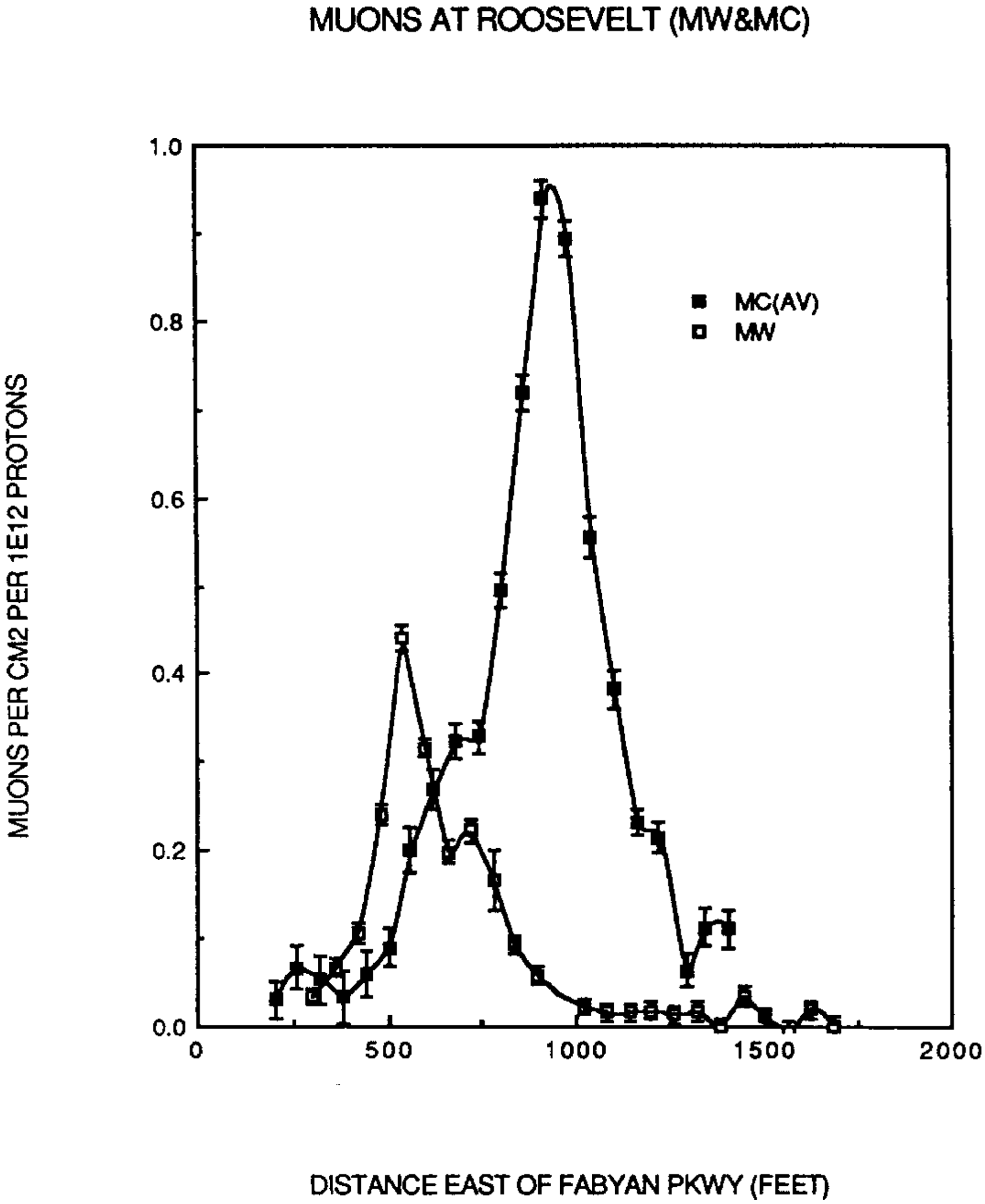

MUONS AT ROOSEVELT (MW&MC)
MC(AV)
MW
MUONS PER CM2 PER 1E12 PROTONS
DISTANCE EAST OF FABYAN PKWY (FEET)
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000

Fig. 3

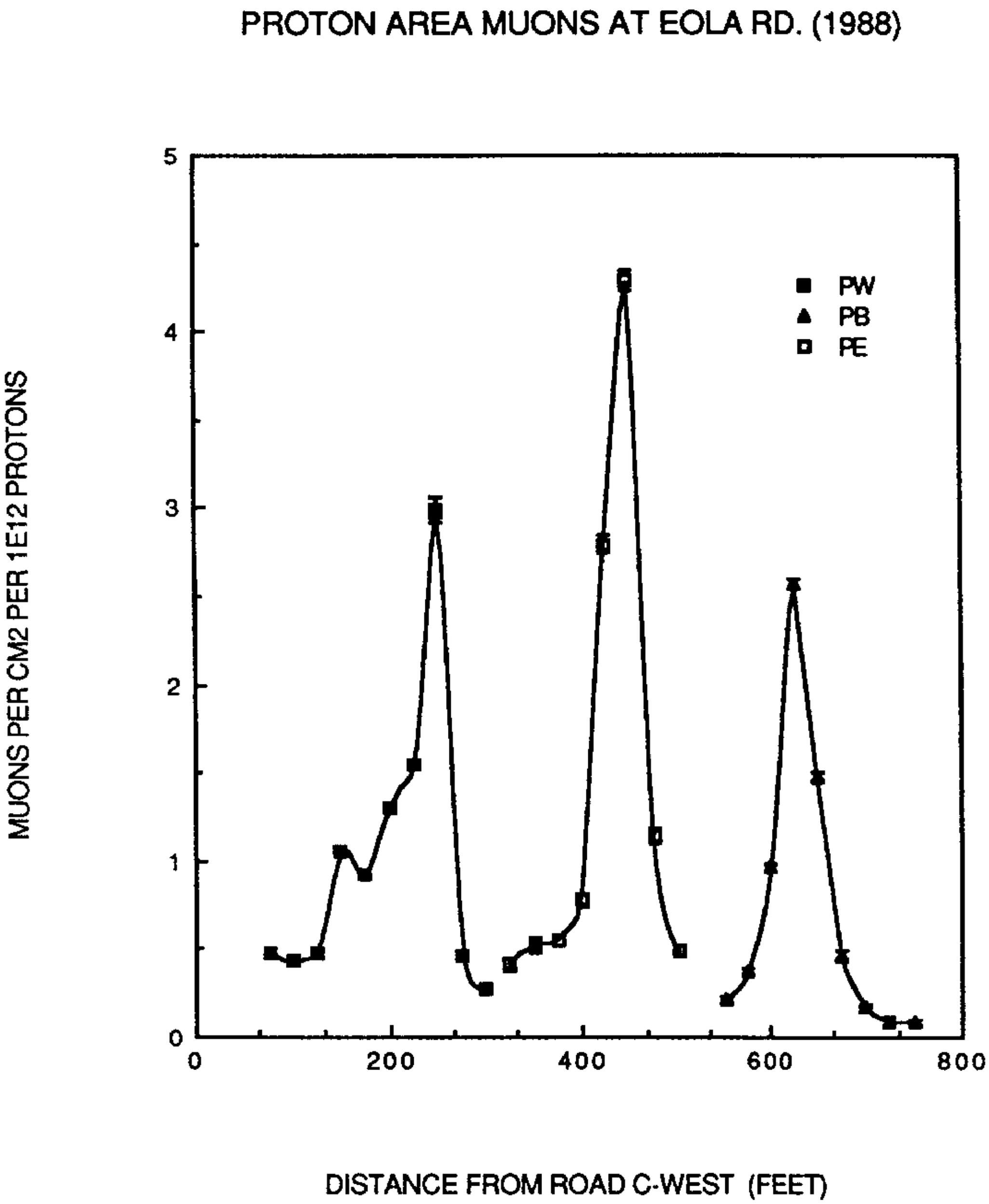
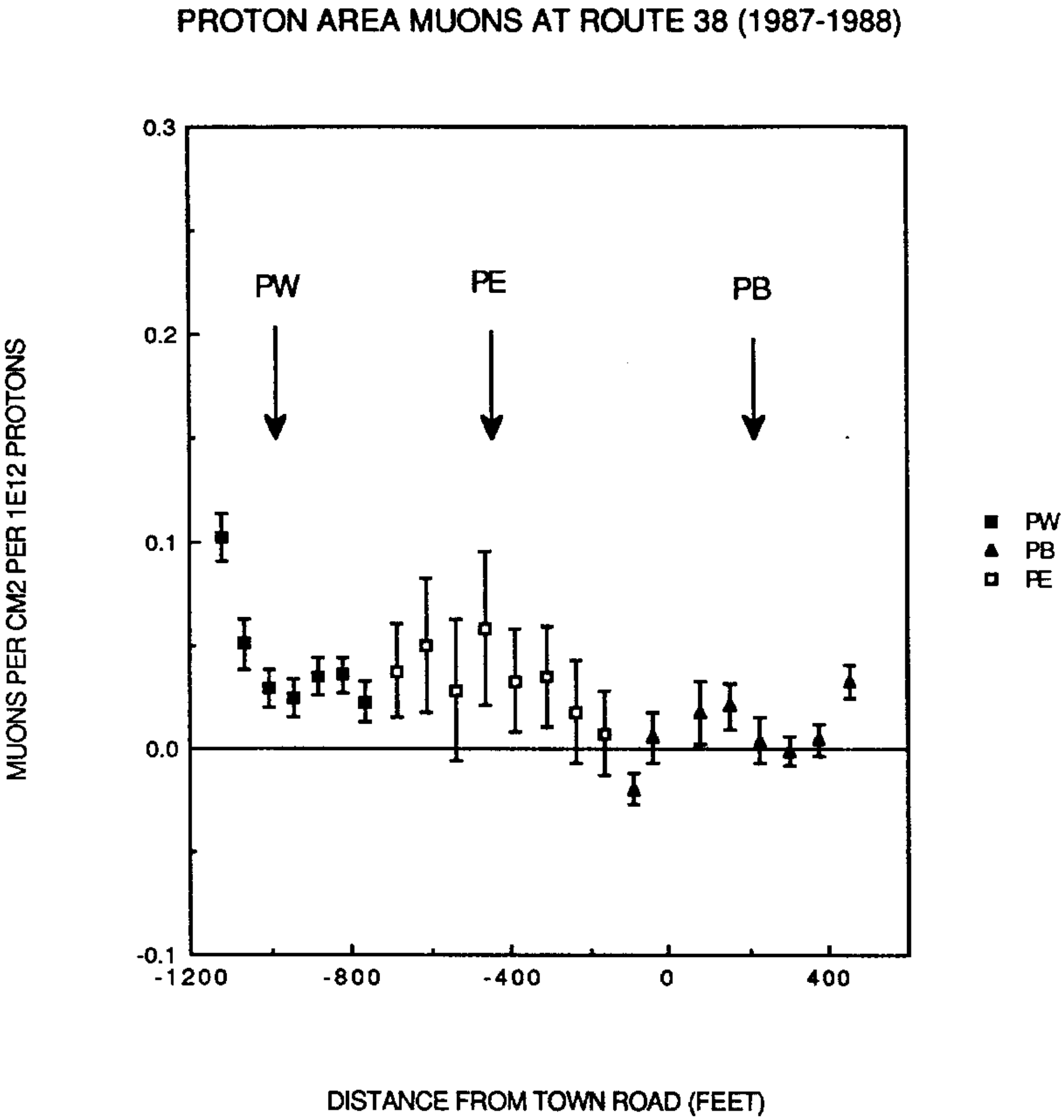

PROTON AREA MUONS AT EOLA RD. (1988)
MUONS PER CM2 PER 1E12 PROTONS
0
1
2
3
4
5
0
200
400
600
800
PW
PB
PE
DISTANCE FROM ROAD C-WEST (FEET)

Fig. 4



PROTON AREA MUONS AT ROUTE 38 (1987-1988)
PW
PE
PB
0.3
0.2
0.1
0.0
-0.1
-1200
-800
-400
0
400
MUONS PER CM2 PER 1E12 PROTONS
DISTANCE FROM TOWN ROAD (FEET)
PW
PB
PE

Fig. 5

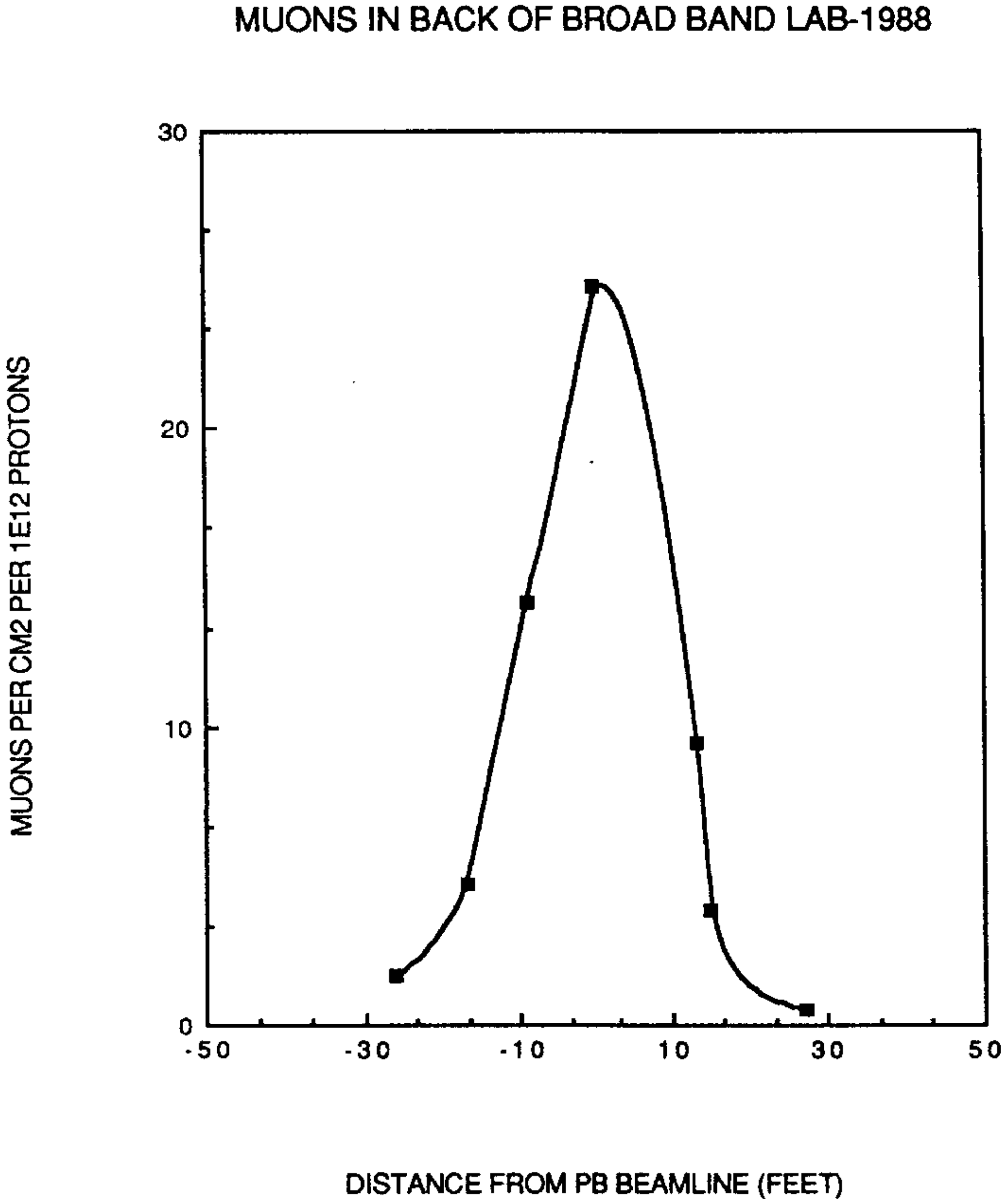

MUONS IN BACK OF BROAD BAND LAB-1988
MUONS PER CM2 PER 1E12 PROTONS
0
10
20
30
-50
-30
-10
10
30
50
DISTANCE FROM PB BEAMLINE (FEET)

Fig. 6

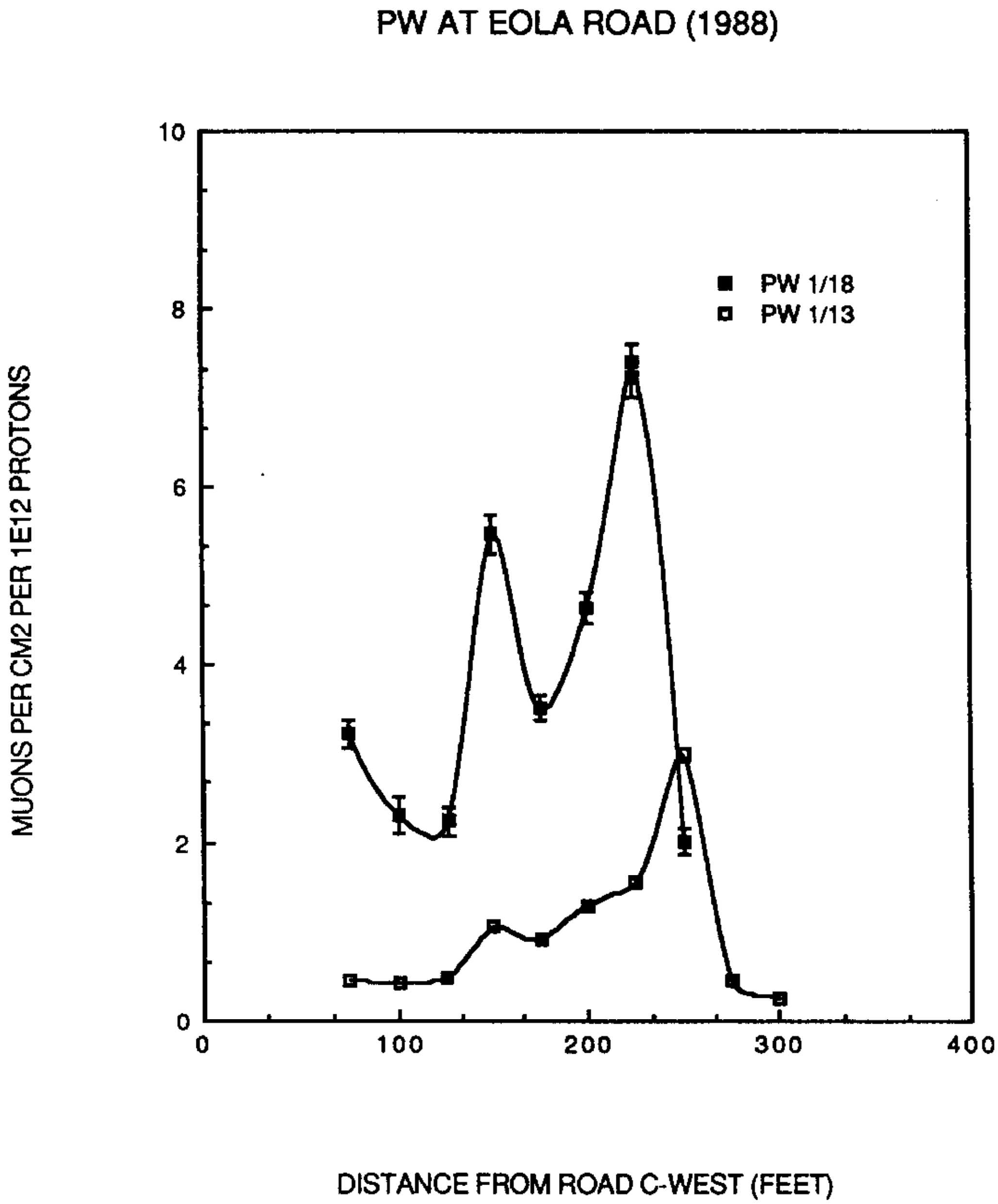

PW AT EOLA ROAD (1988)
PW 1/18
PW 1/13
MUONS PER CM2 PER 1E12 PROTONS
DISTANCE FROM ROAD C-WEST (FEET)
0
2
4
6
8
10
0
100
200
300
400

Fig. 7

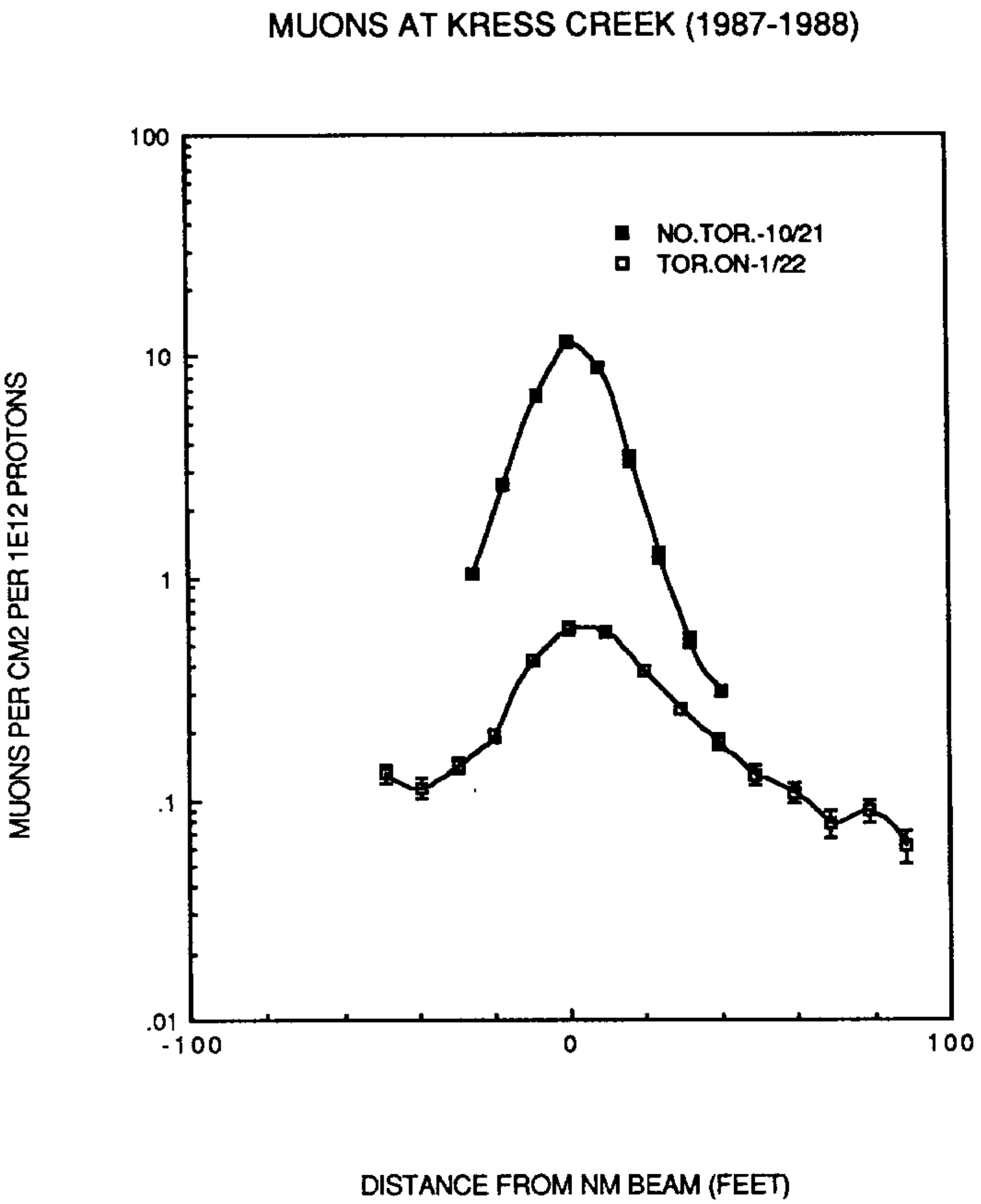

MUONS AT KRESS CREEK (1987-1988)
NO.TOR.-10/21
TOR.ON-1/22
MUONS PER CM2 PER 1E12 PROTONS
100
10
1
.1
.01
-100
0
100
DISTANCE FROM NM BEAM (FEET)

Fig. 8

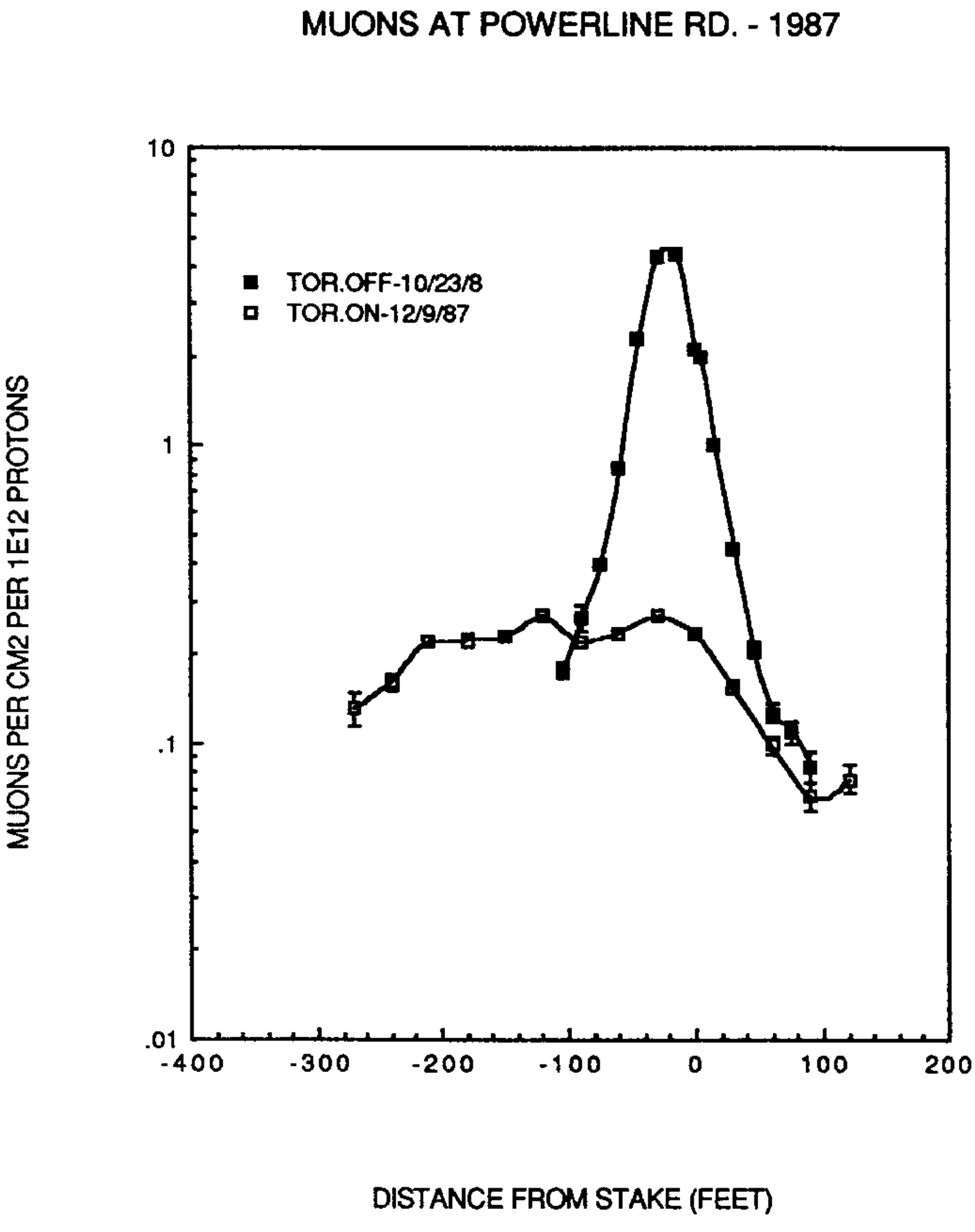

MUONS AT POWERLINE RD. - 1987
TOR.OFF-10/23/8
TOR.ON-12/9/87
MUONS PER CM2 PER 1E12 PROTONS
DISTANCE FROM STAKE (FEET)
10
1
.1
.01
-400
-300
-200
-100
0
100
200

Fig. 9

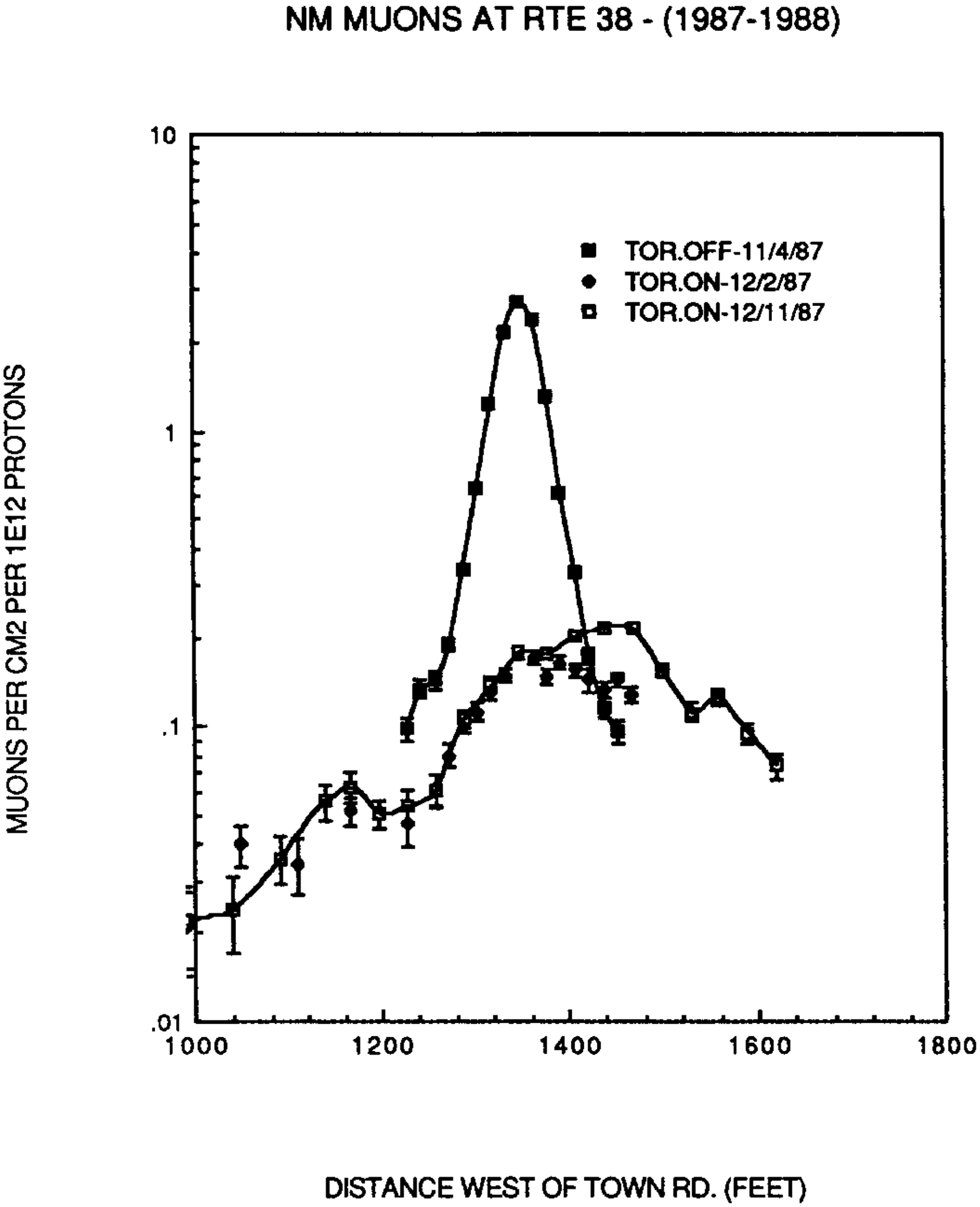

NM MUONS AT RTE 38 - (1987-1988)
TOR.OFF-11/4/87
TOR.ON-12/2/87
TOR.ON-12/11/87
MUONS PER CM2 PER 1E12 PROTONS
10
1
.1
.01
1000
1200
1400
1600
1800
DISTANCE WEST OF TOWN RD. (FEET)

Fig. 10

MUONS IN BACK OF MUON LAB (1987)

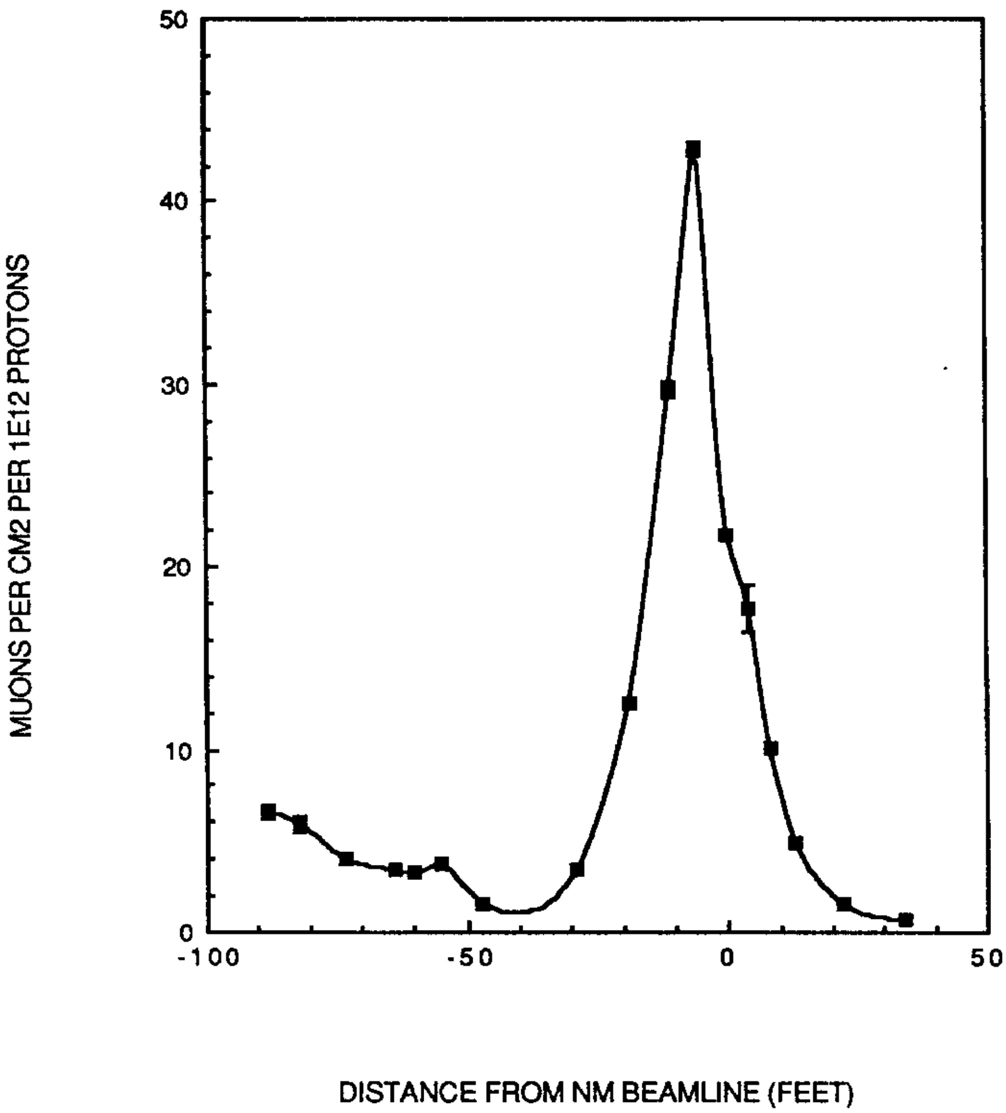
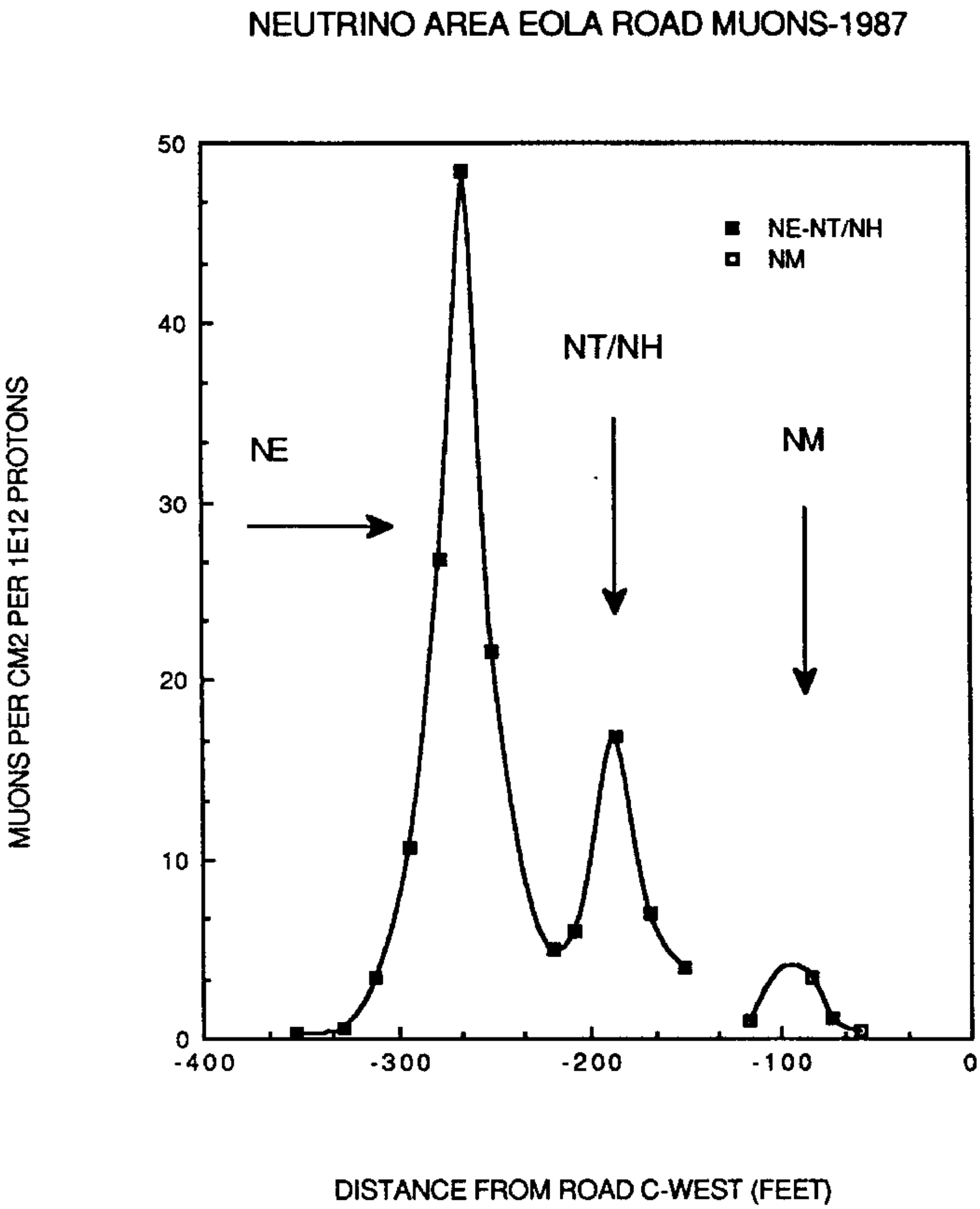


Fig. 11



NEUTRINO AREA EOLA ROAD MUONS-1987
MUONS PER CM2 PER 1E12 PROTONS
DISTANCE FROM ROAD C-WEST (FEET)
NE-NT/NH
NM
NE
NT/NH
NM
50
40
30
20
10
0
-400
-300
-200
-100
0

Fig. 12

MUONS AT POWERLINE RD. DURING NM LAB ACCESS

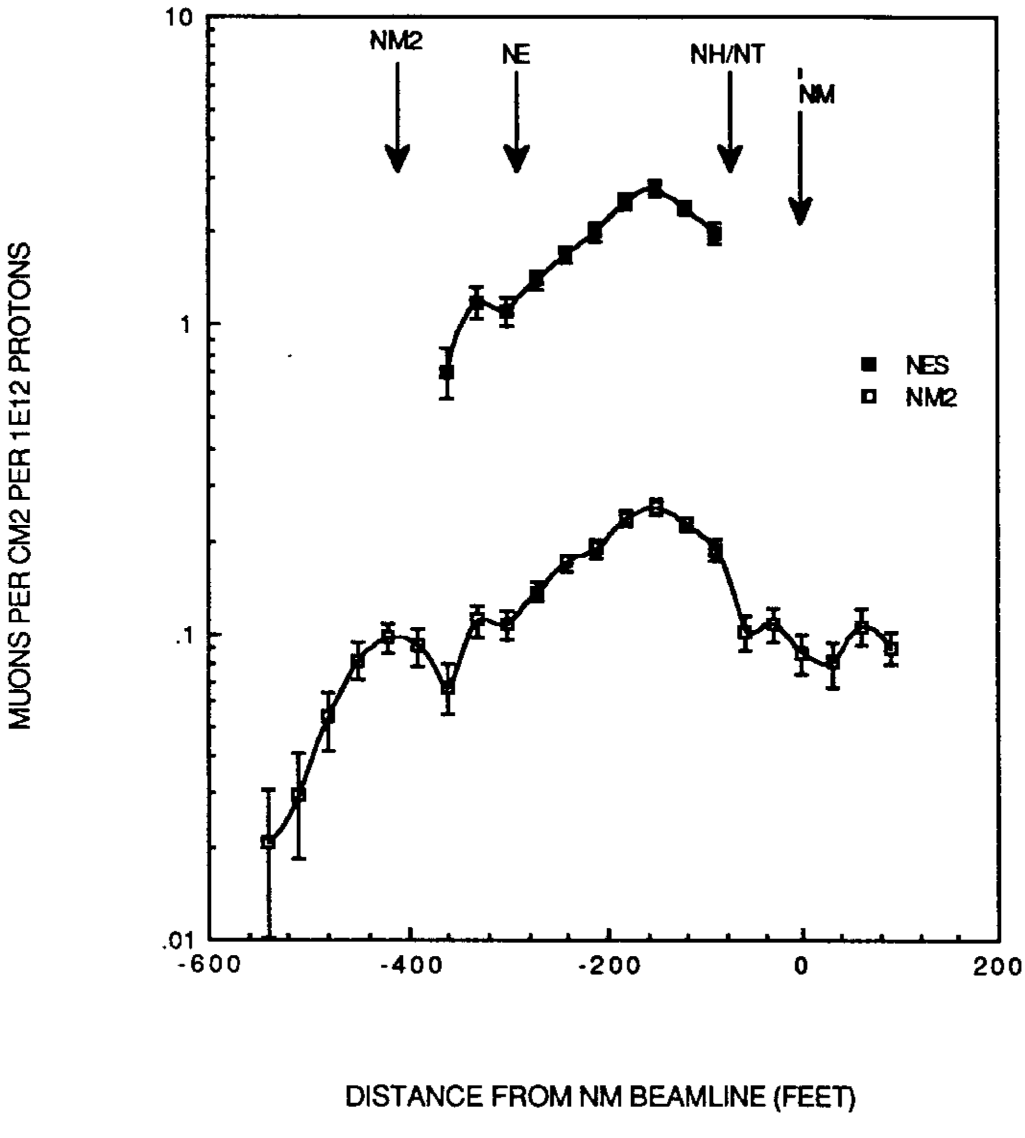


Fig. 13